Structural Vibration Testing of the Lumbar Spine:

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Structural vibration testing of the lumbar spine: development of a diagnostic tool for assessment of segmental stiffness

SUMMARY

Structural vibration testing is a measurement technique that is used in engineering to examine the condition of structures, such as bridges and airplanes. The basic idea behind structural vibration testing is that damage will alter the stiffness, mass or energy dissipation properties of a system, which in turn will change the dynamic response of the system when it is excited with a forcing function. Also damage of spinal structures is followed by alterations in stiffness, which might lead to spinal deformities and low-back pain. Yet, a specific diagnosis is made in only a small minority of patients, and this may be due to the lack of diagnostic tools to pinpoint the structures involved. Since structural vibration testing is non-destructive and requires only low forces and small deformations to detect changes in the mechanical properties it is considered a promising technique to study spinal mechanics.

The aim of this thesis is to study structural vibration testing of the lumbar spine for the assessment of segmental stiffness and to examine whether this methodology may be developed into a clinical tool that is applicable in the diagnosis and evaluation of treatment of spinal deformities, degenerative disc disease and low back pain.

Typical diagnostics of low-back pain rely on physical examination, occasionally extended with imaging. Moreover, while many interventions address the mechanical properties of the joint, these are not measured or are not measured accurately. **Chapter 2** examined the measurement error that might result from using current per-operative measurement devices that take only the loading and deflection of a single segment into account. A stochastic mechanical model was constructed to investigate the effect of measuring an isolated single segment compared to measuring a single motion segment in an intact spine. The study showed that stiffness estimates obtained by loading a single segment in an intact spine are highly correlated with actual stiffness, but overestimate stiffness by a median of 18%. Moreover, the stiffness within degenerated spines was shown to vary largely, which can cause errors up to 400%, and might lead to erroneous surgical decisions.

In **Chapter 3** the feasibility of structural vibration testing for the assessment of intervertebral stiffness was examined. To study the modal characteristics of the spine, goat single motion segments without muscle tissue were tested in vitro. Large structural disruptions were created consecutively by removing the ligaments and creating a hole in the annulus fibrosus. The results showed that removal of the ligaments caused no significant changes in the mode shapes and eigenfrequencies, but the hole in the annulus decreased the eigenfrequency of the torsion mode, thus torsion stiffness. This study also showed that a motion segment, which is not a linear structure, behaves linear if only small forces and deformations are applied. This implies that structural vibration tests and modal analysis techniques can in principle be applied in the spine.

In **Chapter 4**, structural vibration tests were performed on human motion segments. Although the type of structural damage was identified successfully in Chapter 3, the question remained whether vibration analysis can also be applied to human motion segments with structural alterations that occurred naturally. The specimens were tested under similar conditions as in Chapter 3, but the segments were also tested quasi-statically to obtain 'gold standard' static stiffness values. The results showed clear frequency response peaks indicating that vibration testing is also feasible in human motion segments. In addition, an increase in the force amplitude by a factor two resulted in an equally large increase in the response amplitude, indicating that the system behaved linearly. Moreover, the eigenfrequencies were significantly correlated to the static stiffness values, which is an important finding since it suggests that eigenfrequencies provide a valid measure of segmental stiffness. A second important implication of the correlation between static stiffness values and eigenfrequencies is that it shows that eigenfrequencies have the potential to discriminate between different levels of degeneration just as static stiffness values can. The advantage of eigenfrequencies over static stiffness values is that eigenfrequencies can be obtained with small forces and deformations and might therefore offer a safe approach for assessment in patients.

Since Chapter 3 and Chapter 4 showed that the presence of specific structural damage can be assessed with vibration testing and modal analysis, the next step was locating the damage. Damage localisation requires modal analysis and parameter estimation techniques, especially when baseline stiffness information is not available. The mode-shape based parameter estimation technique that was used in this thesis was model updating. Model updating requires the construction of an analytical vibration model based on material properties and geometrical information. The model that was used in this thesis is described in **Appendix I**. **Chapter 5** describes how model parameters of the lumbar spine can be obtained from quantitative computed tomography. A sensitivity analysis was performed to establish the necessary accuracy of the model parameters to ensure successful estimation of the stiffness values. The sensitivity analysis revealed that the modal parameters of the model were most sensitive to changes in vertebral height and mass and joint stiffness. This implies that the presented model can be used for model updating of the stiffness matrix, provided that the parameter values for vertebral height and vertebral mass are sufficiently accurate.

Chapter 6 describes the actual model updating procedure. The lumbar spines of six Dutch milk goats were injected with chondroitinase-ABC to create mild degeneration at random levels, their lumbar spines were harvested and the spinal mechanics were tested statically and dynamically. Vertebral height could be measured on MR-images; vertebral mass was calculated from vertebral height, based on the relation between mass and height that was found in the previous chapter. These subject specific values were used to parameterize the model, as well as average values over six goats from the previous chapter for inertia and location of the vertebral centre of mass. Unfortunately, model updating resulted in a suboptimal fit between experimental vibration data and numerical vibration data as was assessed with the Modal Assurance Criterion (*MAC*) and the residual of analytical and experimental eigenfrequencies. Most likely this was due to inaccuracies in the estimated vertebral mass. The segmental levels with the lowest estimated stiffness values corresponded in 50% of the cases to the levels with the lowest static stiffness, which means that it is not possible to identify the degenerated levels with sufficient certainty. Although these results were disappointing, they also indicate that the proposed methodology can work, provided that better estimates of vertebral mass are obtained.

In conclusion, in this thesis the complexity of the spine was reduced to a system containing just springs and masses. Using this simplification, this thesis shows that structural vibration testing and modal analysis is feasible in the lumbar spine and that it is a reliable and valid method to obtain damage specific information on segmental stiffness, also in naturally degenerated segments. Although it was not possible to localize degenerated segments within the spine, this thesis shows a feasible approach

for such a measurement method and plausible directions for further improvement of the methodology. With future efforts, this methodology may be developed into a clinical tool for the diagnosis and evaluation of treatment of low-back pain.